BIOMIMETIC AND BIO-ENABLED MATERIALS SCIENCE AND ENGINEERING

This special issue of the Journal of Materials Research contains articles that were accepted in response to an invitation for manuscripts.

Introduction

Guest Editors:
Adrian B. Mann
Rutgers University, Piscataway, New Jersey 08854

Rajesh R. Naik
Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio 45433-7750

Hugh C. DeLong
Air Force Office of Scientific Research, Arlington, Virginia 22203

Kenneth H. Sandhage
Georgia Institute of Technology, Atlanta, Georgia 30332-0245

Since humans first walked the Earth they have used structural materials derived from Nature to make tools, weapons, textiles, and dwellings. Even in ancient times there was recognition that Nature offered more than just an abundant source of materials; it offered ideas. Looking at how Nature solved a problem may have helped early inventors solve countless problems related, for instance, to building a boat, making a shield, or constructing a house. One of history's great inventors, Leonardo da Vinci, is famous for his studies of living forms and for his inventions, which were often based on ideas derived from Nature.[1] The lessons learned by da Vinci and others were, of course, not always successful, as seen in the countless efforts throughout the ages by humans to fly like a bird. Nonetheless, these are the origins of human's seeking to solve problems by mimicking Nature. In modern terms we tend to call this field "biomimetics," which essentially means we are seeking to replicate some or all of the features of a biological system. This is of huge importance in medicine where biomimetic solutions are used to treat a range of diseases and conditions. It is known, for instance, that various materials (often derived from Nature) have been used to mimic the form and function of teeth for millennia.[2] In medicine our understanding of the human body's anatomy and physiology has greatly improved over the past 100 years. This has led to dramatic improvements in our ability to replicate the form and function of human tissues using artificial materials. In the latter half of the 20th century, this ability to replicate human tissue has been the most striking advance in biomimetics. The approximate development of biomimetics over the course of human history is shown schematically in Fig. 1.

DOI: 10.1557/JMR.2008.0418

In many ways developments in biomimetics have always been limited by our ability to characterize biological systems and our ability to replicate them. Thousands of years ago all that could be seen was the macroscale structure of biological systems; hence, it was these macroscale structures that humans sought to replicate. Improved characterization and understanding of the structure, chemistry, and function of biological systems has in turn enabled the synthesis of artificial materials that mimic both their structural form and their function. This has arguably reached its zenith now that we our able to characterize biosystems at the level of atoms and molecules while simultaneously, through the advent of nanotechnology, we are able to design materials on the same atomic and molecular scale. One result of this is that biomimetics has been taken in a whole new direction harnessing the power of biosynthesis techniques. Traditionally biomimetics has involved making artificial materials that replicate biological systems, but now it is possible to utilize biomolecules (nucleic acids, proteins, glycoproteins, etc.) and microbes (archaea, bacteria, fungi, protista, viruses, and symbionts) to actually fabricate artificial materials. This development has the potential to revolutionize nanotechnology because biosystems synthesize inorganic materials like apatites, calcium carbonate, and silica with nanoscale dimensions. Beyond the synthesis of nanomaterials, biological systems possess the ability to assemble nanoparticles into larger structures (e.g., bones and shells), effectively performing large scale integration of the nanoparticles. For scientists and engineers the scaling up of nanoparticles into large structures is possibly even more challenging than making nanoparticles. Replication of these bioassembly processes promises to be an enormously fruitful area of research.

In this focus issue of the *Journal of Materials Research* a group of papers is presented that gives a snapshot of

CAMBRIDGE JOURNALS
http://journals.cambridge.org Downloaded: 02 Nov 2012 IP address: 130.207.50.154

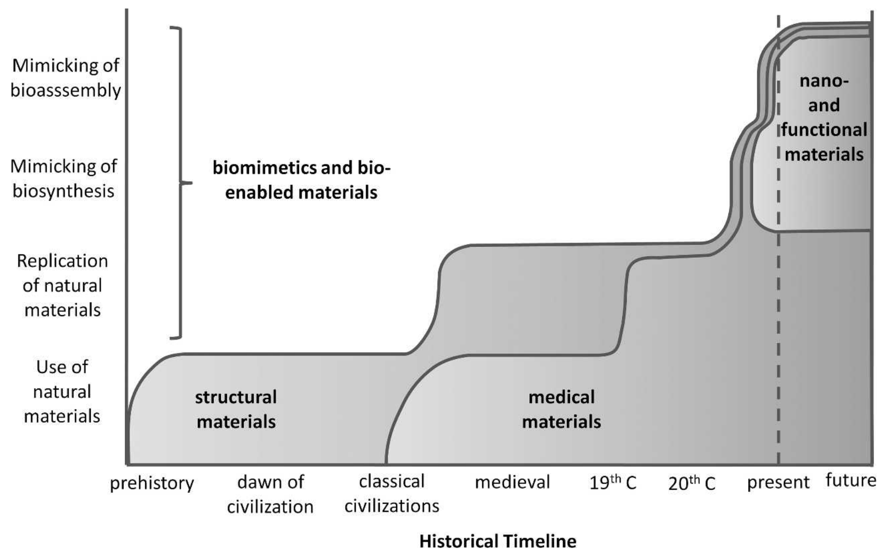

FIG. 1. Natural materials like wood and bone have been used in structural applications throughout the history of the human race. Biomimetics first appeared in ancient times when natural materials and structures were replicated using artificial materials like metals and ceramics. In more recent times biomimetic materials have found applications in medicine where artificial materials have been developed that to some degree replicate the tissues they replace. Currently, the advent of nanotechnology and advances in our understanding of biological systems has enabled the methods of biological synthesis and assembly to be applied in material fabrication. This has greatly expanded the range of materials and the range of applications to which biomimetics is applicable.

current research in biomimetics and bioenabled materials. The papers span all of the methods and applications of biomimetics, though there is naturally an emphasis on the areas that are currently receiving the greatest attention. There are papers on fundamental topics such as molecular level interactions and the characterization of biological materials. Other papers are focused on specific applications, for example, a group of papers concerned with the synthesis of apatites, the main inorganic component of bones and teeth. The interest in apatite stems largely from the medical need for new and better materials for orthopedic and dental applications. This is a need that is growing rapidly with the aging populations of many developed countries.

Apatite is a common crystalline form of calcium phosphate, found in mineral form in several places as fluorapatite. In living systems it is defective hydroxyapatite that is the inorganic component of mineralized tissues. Materials scientists and engineers can synthesis artificial hydroxyapatite by a wide range of techniques, but these frequently involve high temperatures or other extreme conditions. It is remarkable that biological systems are able to synthesis hydroxyapatite crystals of highly controlled geometry, variable stoichiometry, and to assemble them into complex structures all at temperatures of around 37 °C. This is just one example of how biology is able to process materials with greater control and more efficiency than materials scientists and engineers. The astonishing ability of biological systems to synthesis materials stems from their chemical, physical, and morphological complexity. This is discussed in the review paper by Vincent[3] who examines the idea that artificial materials are typically made using large amounts of energy while biological systems circumvent this by using information in materials synthesis. The information being encoded in the structure of biosystems from the level of molecules upwards.

The area where biomimetics and bioenabled materials promise to have the greatest impact lies in making and assembling nanomaterials. Biomolecules and cells can be remarkably selective in their binding, which can make them useful in templating and regulating nanomaterials synthesis. As well as being highly selective they also offer immense diversity. The 20 most common amino acids[4] can be combined to form literally thousands of different polypeptides, all with different affinities and conformations. Add to this nucleic acids, glycoproteins, and various other biomolecules, and quickly it becomes apparent that the diversity is vast. At a larger scale there are a huge range of viruses, prokaryotic cells (bacteria and archea), and eukaryotic cells, which might be used in materials synthesis and assembly. The real challenge facing researchers in this field then is identifying which molecule, virus, or cell to use. One solution is to adopt a combinatorial approach where a wide range of molecules or cells are used to see if they can perform the desired function. An alternative approach is to use a predictive model so that an appropriate biosystem can be chosen. This, however, raises the specter of understanding and modeling organic–inorganic interfaces, which is extremely challenging in its own right.

At the beginning of the 21st century, it is fair to say that biomimetics is ancient in its origin, but modern in

CAMBRIDGE JOURNALS
http://journals.cambridge.org Downloaded: 02 Nov 2012 IP address: 130.207.50.154

terms of its potential applications and use. This area of materials research is set for rapid expansion in coming years, and this will result in substantial technological advances.

The editors wish to thank the Materials Research Society for embracing the field of biomimetics and bioenabled materials through a series of MRS Symposia on related topics.[5,6] Recently, MRS has also been active in promoting this exciting area of research through two issues of *MRS Bulletin* published in 2008.[7,8] We especially thank Dr. Gordon Pike, the *JMR* Editor-in-Chief, for allowing us to pursue this focus issue; we thank also the *JMR* staff, especially Linda Baker and Eileen Kiley Novak, for technical assistance through all aspects of the project. Finally, we thank the many participants in this issue, including contributors representing a wide range of research topics and reviewers from many backgrounds for their efforts in this issue and, more generally, for their efforts in this growing field.

REFERENCES

1. Leonardo da Vinci: *Leonardo's Notebooks*, edited by H. Anna Suh (Black Dog & Leventhal Publishers, New York, 2005).
2. J. Schmidseder: *Aesthetic Dentistry* (Thieme, New York, 2000), p. 1.
3. H. Lodish, A. Berk, S.L. Zipursky, P. Matsuaira, D. Baltimore, and J. Darnell: *Molecular Cell Biology* (W.H. Freeman & Company, New York, 2007), p. 52.
4. J.F.V. Vincent: Biomimetic materials. *J. Mater. Res.* **23**(12), xxxx (2008).
5. *Biological and Biomimetic Materials—Properties to Function,* edited by J. Aizenberg, J.M. McKittrick, C.A. Orme, and P.G. Vekilov (Mater. Res. Soc. Symp. Proc. **724,** Warrendale, PA, 2002).
6. *Biological Materials to Biomimetic Material Synthesis*, edited by N. Kröger, R. Qiu, R. Naik, and D. Kaplan (Mater. Res. Soc. Symp. Proc. **1094E,** Warrendale, PA, 2008).
7. Biomolecular mimetics. *MRS Bull.* **33**(5) (2008).
8. Bioinspired materials for self-cleaning and self-healing. *MRS Bull.*, **33**(8) (2008).

CAMBRIDGE JOURNALS
http://journals.cambridge.org Downloaded: 02 Nov 2012 IP address: 130.207.50.154